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Demonstration and Analysis of Reusable Launch Vehicle Operations

John Garvey

Garvey Spacecraft Corporation
389 Haines Avenue
Long Beach CA 90814

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SBIR Phase I Final Report

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FOR THE DIRECTOR:

//Signature//

RICHARD K. COHN
Program Manager

//Signature//

SHAWN H. PHILLIPS
Chief, Engine Branch

//Signature//

PHILIP A. KESSEL
Technical Advisor, Space and Missile
Propulsion Division

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GLOSSARY

AFRL/PR	Air Force Research Laboratory / Propulsion Directorate
AGL	above ground level
CALVEIN	California Launch Vehicle Education Initiative
Cal Poly SLO	California Polytechnic State University, San Luis Obispo
CSULB	California State University, Long Beach
DOD	Department of Defense
DV	digital video
EAFB	Edwards Air Force Base
ENLV	expendable nanosat launch vehicle
ESLV	expendable small launch vehicle
FAR	Friends of Amateur Rocketry, Incorporated
ft	feet
ft/s	feet / second
GHe	gaseous helium
GLOW	gross liftoff weight
GN2	gaseous nitrogen
GSC	Garvey Spacecraft Corporation
HNLV	hybrid nanosat launch vehicle
HSLV	hybrid small launch vehicle
ISP	specific impulse
kg	kilogram
km	kilometer
LEO	low Earth orbit
LOX	liquid oxygen
lbf	pound – force
lbm	pound - mass
MSU	Montana State University
N	Newton
NLV	Nanosat Launch Vehicle
P	Prospector
P-POD	Poly-Picosat Orbital Deployer
psi	pounds per square inch
RLV	reusable launch vehicle
SBIR	Small Business Innovation Research
SLV	small launch vehicle
s, sec	second
T	time (relative to start of flight) in seconds unless otherwise specified

1.0 INTRODUCTION

The increased use of reusable systems continues to be one of the most promising options for creating "... advancements in the daily maintenance of rocket systems, lowering hours for preparation and diminish[ing] expenses for preparation. ..." The pioneering DC-X/XA Delta Clipper program demonstrated the effectiveness of employing a robust flying test bed for evaluating such factors as they relate to reusable launch vehicle (RLV) designs, technologies and operations.

Several projects in the decade since the Delta Clipper program - notably the X-33, X-34 and X-37 - have attempted to address the continued need for follow-on RLV flight testing, particularly in the area of operations. Despite extensive funding, all three programs experienced major technical difficulties due to a combination of overly ambitious performance requirements and the incorporation of too many complex technologies into a single airframe. Consequently, none of these vehicles even made it to the launch pad before being terminated and RLV developers have been deprived of the opportunity to research key operational parameters.

This Phase I Small Business Innovation Research (SBIR) project has provided an opportunity to quickly jump-start domestic RLV flight-based test and evaluation through the innovative use of a proven test vehicle design originally developed, flown and recovered through the California Launch Vehicle Education Initiative (CALVEIN). Specifically - it resulted in the demonstration of rapid turn-around operations of only 3.5 hours for a prototype of the first stage for a proposed nanosat launch vehicle (NLV) (Figure 1).

This joint industry-academic team is led by Garvey Spacecraft Corporation (GSC) and California State University, Long Beach (CSULB). Our team's current work is focused on flight testing full-scale prototypes of a proposed commercial NLV that could deliver small payloads of up to 10 kg to low Earth orbit (LEO). Both the NLV mission and this initial expendable NLV (ENLV) concept continue to serve as references for defining and evaluating future follow-on RLV-based research opportunities.

Such frequent, incremental development missions like those conducted in Phase I are a key element of our NLV commercialization strategy. Besides validating launch vehicle technologies and operations, they provide multiple opportunities for manifesting early payloads from members of the emerging small satellite community. The growing interest in launch services for this class of payload and the benefits deriving from reuse of experimental hardware are highlighted by the fact that the Phase I prototype RLV has already since been utilized on its third flight to conduct a customer-sponsored technology flight demonstration. This vehicle is now being prepared to carry additional payloads during Phase II. Ultimately, the economic insights obtained through such actual, revenue-generating RLV flight operations could prove to be as significant as the technical results associated with the original demonstration of fast turn-around operations.

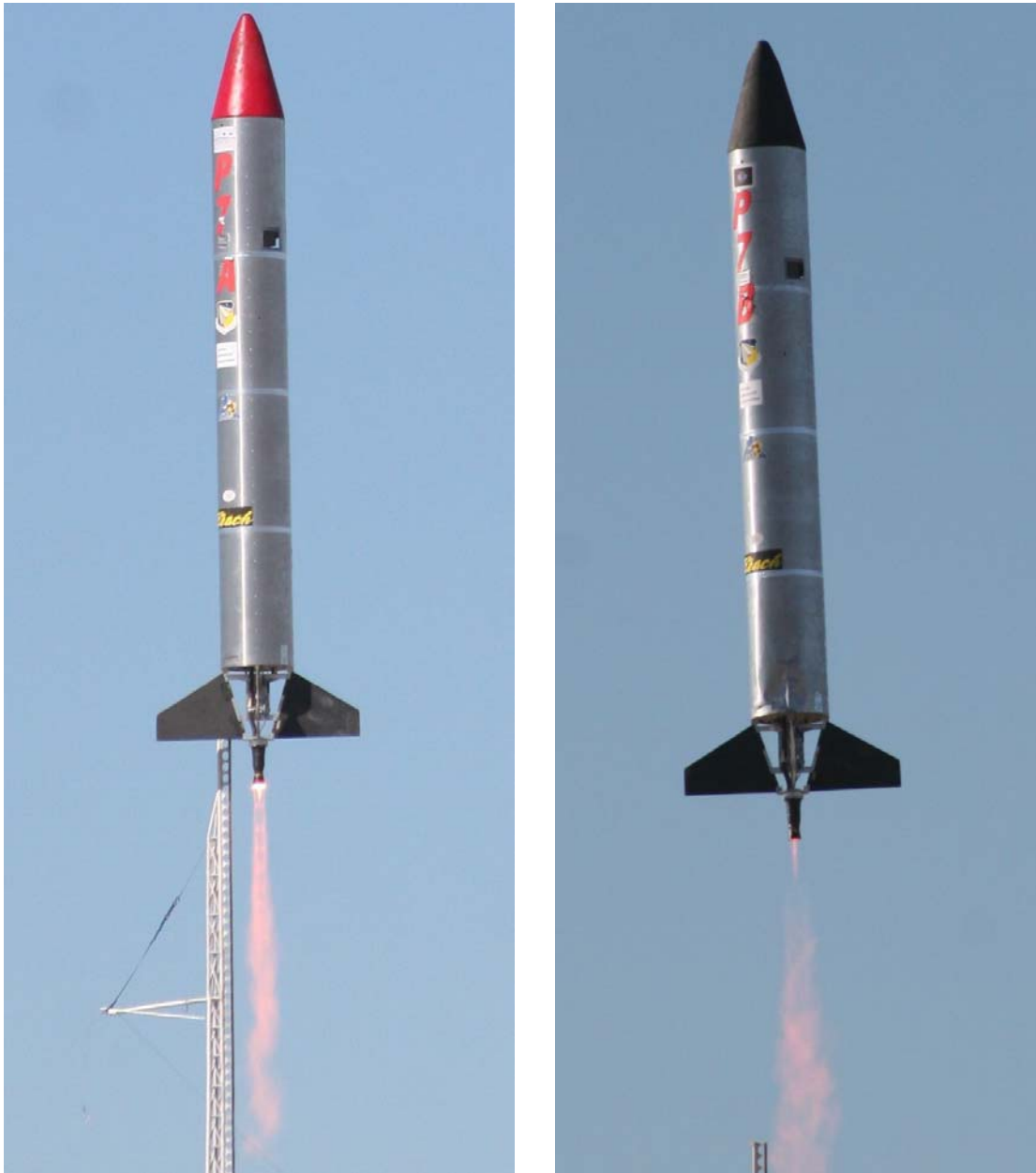


Figure 1: RLV Fast Turn-Around Flights - Twice Within 3.5 Hours

2.0 DISCUSSION OF RESULTS

The discussion here provides a summary of results achieved during Phase I and preliminary extrapolations to full-up operational conditions.

2.1 Program Management

The program kick-off meeting took place on 15 June 2005 at the Air Force Research Laboratory / Propulsion Directorate (AFRL/PR) facilities at Edwards Air Force Base. The Flight Readiness Review and associated hardware inspection took place on 26 October 2005 within the CSULB lab several days prior to the main test activities on 29 October 2005. Total task duration from authority to proceed through the successful completion of flight testing was just six months and included development of an entirely new prototype RLV (the Prospector 7 - "P-7") along with the integration of four academic payloads. In addition, both flights took place as planned on the first day of the original launch window established several months beforehand.

2.2 Requirements Definition

Table 1 presents the flight test mission-level objectives and their status at the end of Phase 1 after completion of the demonstration. Requirements to acquire and quantify process parameters related to RLV turn-around operations are addressed in Section 2.4.

Table 1. Phase I RLV Demonstrator Flight Test Mission Objectives

Primary Objectives	Status
Conduct two flight tests within a 24 hour period using the same prototype RLV	Conducted within 3.5 hours
Monitor and measure key design and operational parameters associated with rapid turn-around launch activities	Completed (Section 2.3)
Secondary Objectives	
Acquire vehicle dynamic and performance data while in flight	Acquired using Montana State University (MSU) data logger
Manifest academic payloads	four academic payloads manifested, with two - the Cal Poly SLO* Poly-Picosat Orbital Deployer (P-POD) and the MSU data logger - functioning nominally on both flights

* California Polytechnic State University, San Luis Obispo

2.3 RLV Demonstrator Design and Development

The decision was made early during Phase I to develop an entirely new prototype test vehicle - the P-7 - rather than adapt the existing Prospector 6 (P-6) for the RLV rapid turn-around flight demonstration. Three factors driving this decision were a) the elimination of Phase I schedule risk related to the P-6 in the event that the latter might become unavailable after its first flight test, b) leveraging lessons learned related to the airframe design and recovery system and c) the opportunity to switch to lighter-weight aluminum fittings and tubing in the P-7 propulsion system.

This approach was validated by the on-budget and on-time development of the P-7 and the subsequent successful fast turn-around flight demonstrations - all conducted within the funding and schedule constraints of a SBIR Phase I project. Furthermore, in another step towards eventual RLV commercialization, the P-7 is already being used for follow-on flight testing sponsored by external customers.

Figure 2 presents the final configuration that was baselined for the P-7. Its design and production heritage traces back to seven Kimbo flight test vehicles originally developed by GSC and another six Prospector-class rockets that have resulted from the GSC/CSULB CALVEIN partnership that has been underway since 2001. The vehicle remains integrated through all phases of flight and recovery and reflects the resolution of the major design issues originally identified at the start of the project (Table 2). Like the earlier Prospector 5 (P-5) vehicle from which the P-7 is directly derived, recovery is achieved by a side-deploying drogue and main parachute combination that is ejected in a single event just after apogee. The most visible distinction from the P-5 is that the P-7 features an interstage, which along with the payload fairing, serves as a replaceable shock absorber for landing.

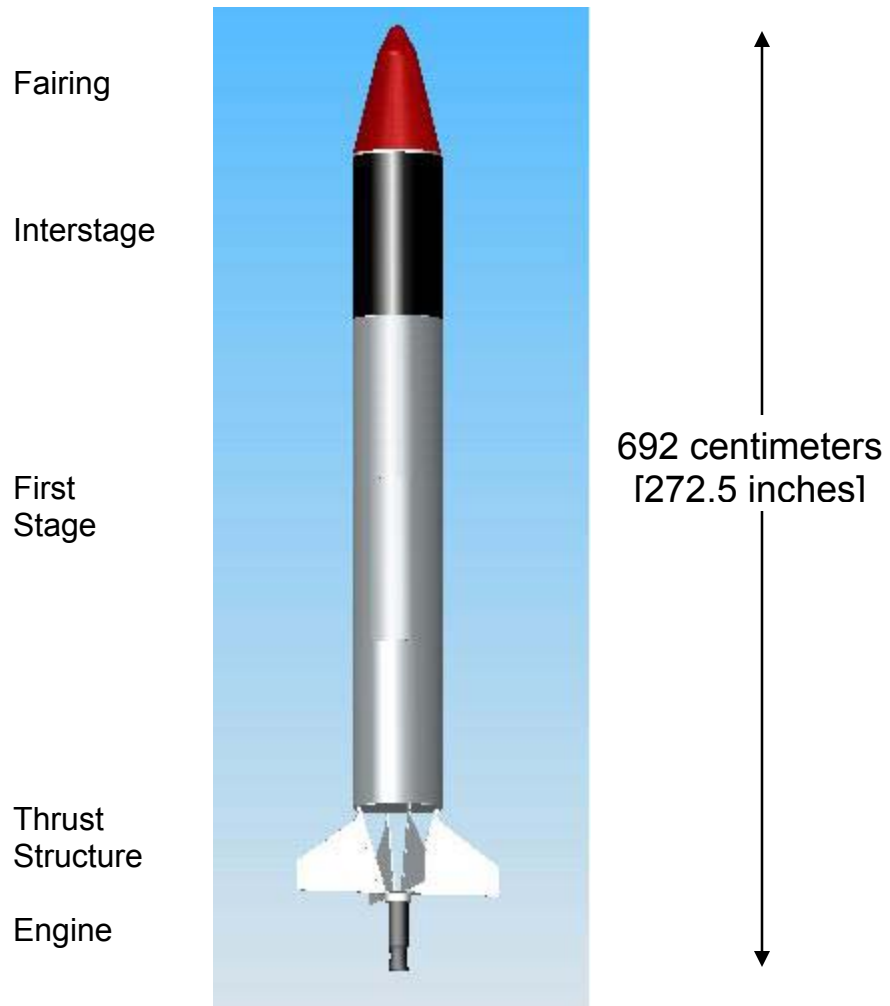


Figure 2: Prospector 7 Configuration

Table 2. Phase I Design Issues

Issue	Resolution
Determine whether to remove the Interstage, which will impact the center of gravity, aerodynamics and parachute attachment points	Retain the interstage, which along with the fairing, absorbs the landing shock
Reduction of landing damage to the fins and thrust structure	Replace damaged fins and thrust structure struts rather than attempt to make them more robust
Determine what hardware can be treated as field-replaceable and/or serviceable, to improve the potential for rapid turn-around flight	Baseline replacing the fairing, interstage, damaged fins and struts, and ablative engine chamber
Telemetry enhancements	Improved Wi Fi telemetry package
Payload accommodations	Manifest the Cal Poly P-POD CubeSat deployer

Tables 3 and 4 document the final mass properties of the P-7 while Figure 3 provides a history of the evolution of these properties through the course of Phase I. To stimulate refinements in the structural design, 270 lbm was established at the beginning of development as the design objective for the gross liftoff weight (GLOW), with separate mass targets allocated for each major vehicle element (first stage, interstage and fairing) but not specifically for any payloads. Margin was maintained by the fact that a GLOW of 300 lbm represented a functional threshold for the existing propulsion system (an even greater GLOW could be accommodated, but would have required upgrades to the propulsion system). The final estimated GLOW was on the order of 289 lbm and included 25.6 lbm of payload.

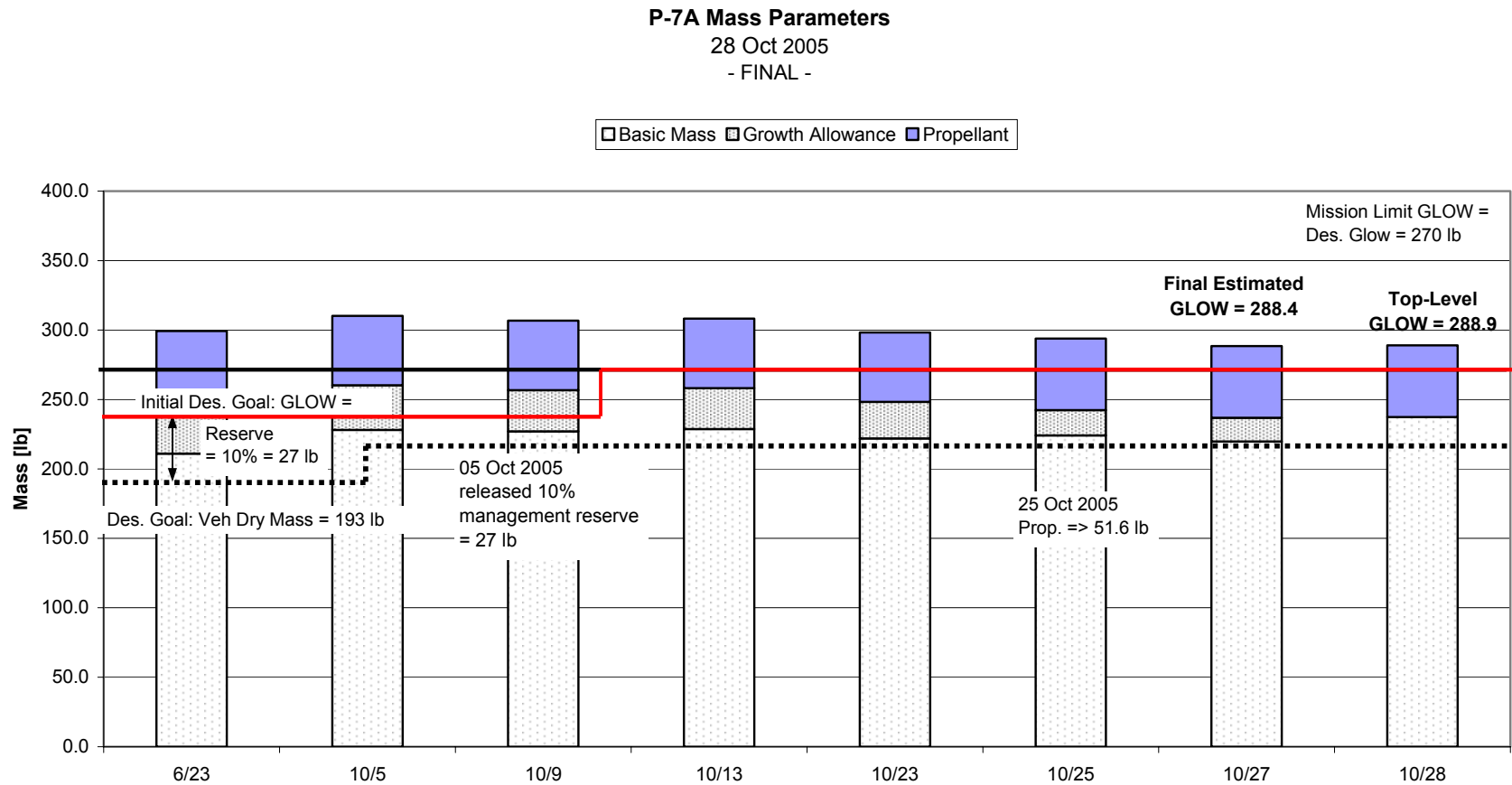
Table 3. Vehicle Weight*

Vehicle Element	Final Estimated Weight [lbm]	Measured Weight [lbm]
First Stage	201.2	200.3
Interstage	28.9	37.0
Payload Accommodations (Fairing)	6.7	
TOTAL DRY WEIGHT	236.8	237.3

* total weight of experimental payloads = 25.6 lbm and is included within the associated stage weights

Table 4. P-7 Mass Summary

Mission Limit - Gross Liftoff Weight [lb]	270.0
Reserve (10 % of ML) [lb]	0.0
Design Goal - GLOW [lb]	270.0
Propellant Mass	51.6
Design Goal - Vehicle Dry Weight [lb]	218.4
Total Basic [lb]	237.3
Growth Allowance [lb]	0.0
Predicted Vehicle Dry Weight [lb]	237.3
<i>Estimated GLOW</i>	288.9
Dry Weight Margin [lb]	-18.9
Percent Dry Weight Margin = Margin / Predicted Vehicle Dry Weight	-9%
Basis	
Actual	100%
Calculated	0%
Estimated	0%

**Figure 3: Vehicle Mass History**

2.4 Payload Identification and Recruitment

Under the scope of Task 4 - Candidate Payload Identification and Recruitment - four university payloads were ultimately manifested on both P-7 flights (Table 5).

Table 5. Academic Payloads Manifested on the P-7

Experiment	Objectives	Provider	Comments	Location
Mini-Digital Video (DV) Camera	acquire in-flight video for post-flight recovery	CSULB	similar to video imaging experiment flown on P-6	aft bulkhead of first stage
Wi Fi-based IMU/GPS Telemetry Package	acquisition and real-time downlink of 6-degree-of-freedom dynamic data, tank pressures and break wire inputs	CSULB	derived from P-6 Wi Fi telemetry experiment, now includes O-Navi Phoenix IMU/GPS unit	dedicated bulkhead at the forward end of first stage, above the liquid oxygen (LOX) tank assembly
Data Logger	acquire vehicle environments and flight dynamics data for post-flight recovery	MSU	enhanced version of MSU data logger flown on P-6	aft bulkhead of first stage
Prototype P-POD	demonstrate CubeSat integration and deployment	Cal Poly SLO	features P-POD similar to that which will fly on Dnepr launcher	dedicated bulkhead at the aft end of the interstage

The MSU data logger functioned well on both flights, generating impressive sets of data (several examples of which are presented in section 2.5.2). It was recovered intact after the second flight and returned to MSU for future applications. The Cal Poly SLO P-POD also successfully deployed a set of three simulated CubeSats on both flights, at approximately T+37 to 38 seconds. The simplicity of loading the CubeSats in the field validates the potential for this system to become a standard option for operational NLV missions that manifest multiple CubeSats.¹

In contrast, the refurbished mini-DV camera previously flown on the P-6 failed to provide imaging data on either flight. This was attributed to lack of auto adjustment capability for handling bright sunlight conditions during the first flight and drained batteries on the second flight. The enhanced Wi Fi telemetry experiment also failed to operate on either flight, despite extensive diagnostic and repair efforts. Root cause is attributed to inadequate pre-flight preparations and a potential design error in the external-to-internal diode switching circuitry.

2.5 Flight Testing

2.5.1 Operations

Flight operations took place on Saturday, 29 October on the eastern edge of Koehn lake bed after just 18 hours of on-site pre-launch preparations. The vehicle was designated as the Prospector 7A (P-7A) for the first flight and Prospector 7B (P-7B) for the second flight. The primary objective of conducting two flights in a single 24-hour period was accomplished, with only 3.5 hours actually being required.

Figure 4 through Figure 11 show key phases of the field operations, from initial vehicle preparations on the 57-ft deployable launch rail through return of the P-7B vehicle to the launch site. Weather conditions were extremely benign throughout the day with essentially no wind or cloud cover. The most significant challenges prior to first launch were associated with the electrical ground support equipment, which continued to exhibit data drop-outs (the leading root cause of which is now determined to be temperature sensitivity of at least one of the data acquisition modules).

As addressed in more detail in Section 2.4, vehicle performance on the first flight was nominal, with the P-7A achieving a peak altitude on the order of 4,500 ft above ground level (AGL). However, more gaseous helium (GHe) was used than anticipated, resulting in insufficient quantities for conducting the P-7B flight test. The decision was made in the field to utilize gaseous nitrogen (GN2) for propellant tank pressurization instead, with recognition that this could negatively impact the propulsion system's performance. This proved to be the case, with the GN2 flow being overly restricted. Despite the greatly reduced thrust profile and a peak altitude well below 1,000 ft, the recovery system still functioned and returned the vehicle to the ground per plan. Although the nominal peak altitude was not reached due to this substitution of pressurization gases, the technical program objective (demonstrating two launches within 24 hours) was still achieved. The insufficient amount of GHe is a readily solved logistical issue that will be corrected by planning for greater supply margins on future test projects.



Figure 4: P-7A Undergoing Final Launch Preparations



Figure 5: First Flight of the Day



Figure 6: P-7A Just Prior to Landing



Figure 7: Preparations Underway for Second Launch



Figure 8: Second Flight Underway



Figure 9: P-7B Parachute Recovery



Figure 10: P-7B Just Prior to Landing



Figure 11: Returning the P-7B to the Launch Site

2.5.2 Vehicle Performance

Table 6 summarizes the updated performance parameter estimates that are based on flight data acquired by the MSU data logger during the first flight. Figure 12 and Figure 13 provide both the data logger altitude plot, along with refined modeling estimates. The two on-board recovery altimeters and the MSU data logger measurements show decent correlation with respect to a peak altitude on the order of 4500 feet AGL on this flight. Due to the anomaly caused by the switch to GN2 for propellant tank pressurization on the second flight, the P-7B barely managed to get to 750 ft AGL, but this was still sufficient for the recovery system to operate.

Table 6. Updated Model of P-7A Trajectory Events

	Liftoff	Burnout	Apogee	Parachute deployment	Touch-down
Time (s)	0	9	20	24	196
Altitude AGL (ft)	0	2650	4647	4398	0
P_c (psi)	249	183	0	0	0
$P_{tk\ LOX}$ (psi)	420	293	0	0	0
$P_{tk\ fuel}$ (psi)	420	260	0	0	0
Thrust (lbf)	1055	744	0	0	0
Horizontal speed (ft/s)	0	158	98	90	0
Vertical speed (ft/s)	0	453	0	-122	-25

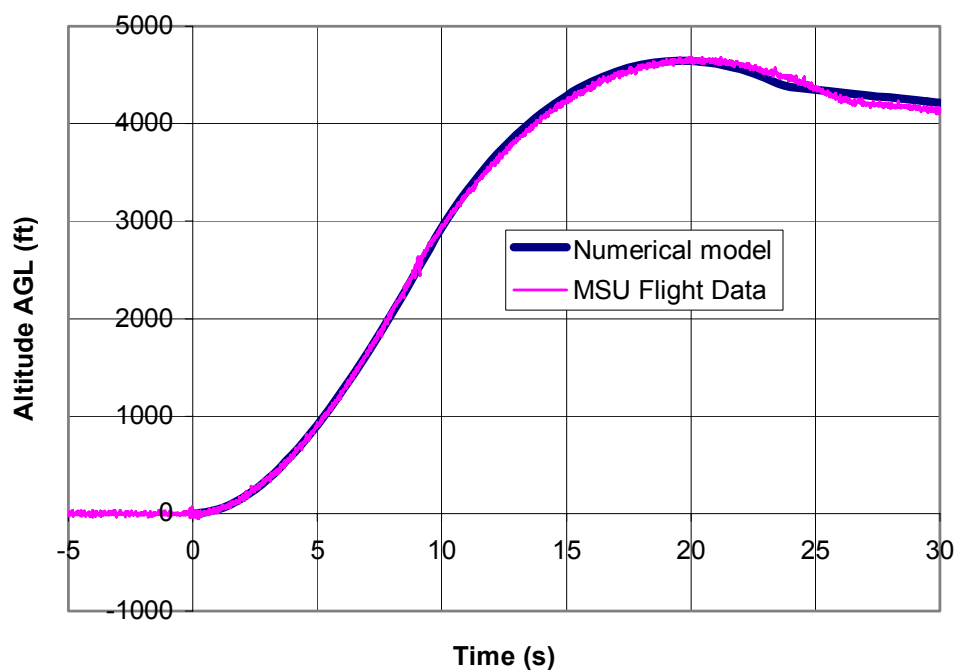


Figure 12: P-7A Flight Profile - From Liftoff to Parachute Deployment

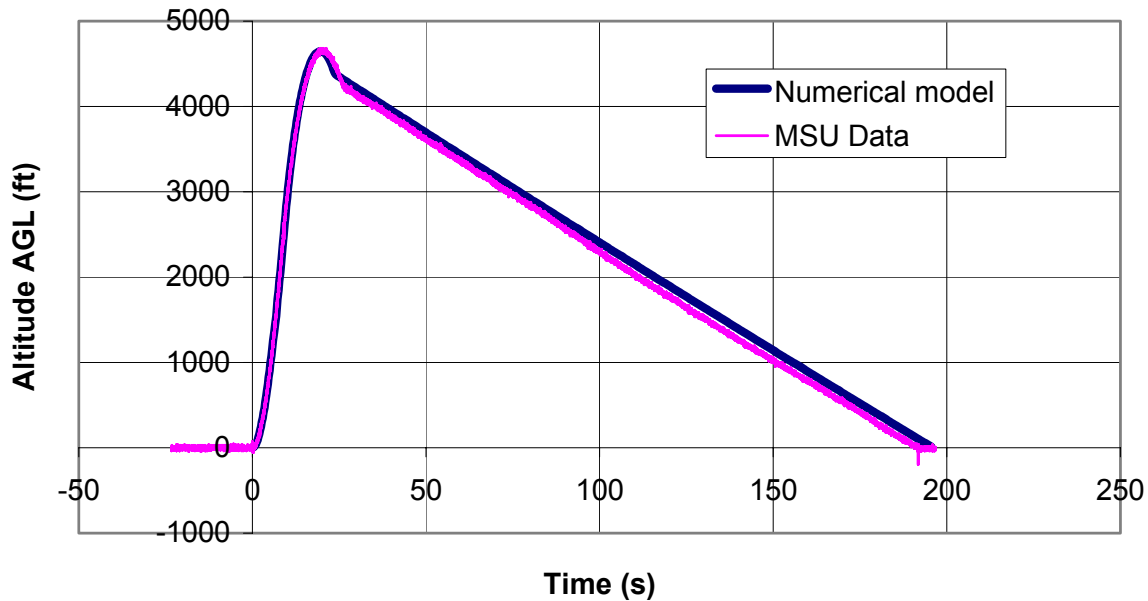


Figure 13: P-7A Flight Profile - From Liftoff to Landing

Of particular significance was the empirical determination that the terminal descent rate under the main parachute was 26 feet per second on both flights, versus the prediction of 19 feet per second. Analysis indicates that the measured descent rate under the main parachute is consistent with another, smaller parachute sold by the parachute vendor. However, inspection re-confirmed that the main parachute is labeled as the one used in the pre-flight estimates. Given that the recovery was within acceptable limits, no corrective changes are planned for future P-7 missions, but pre-flight analysis will include estimates based on the other parachute as well to establish the upper bound of expected descent rates. In addition, improved procurement control will be employed on future vehicle development projects to provide better certainty and traceability regarding parachute parameters.

Despite this higher-than-predicted descent rate, the recovery system returned the vehicle in better overall condition than expected, with only one fin and strut set requiring replacement instead of two. The only non-baseline damage was to the forward mating ring of the first stage - the result of the side load at landing. It was replaced with minimal difficulty and no effect on the overall recovery and refurbishment process.

Figure 14 presents the MSU data for the altitude profile on the second flight of the day and reflects the performance issues associated with the use of GN2 instead of GHe for tank pressurization, as noted previously.

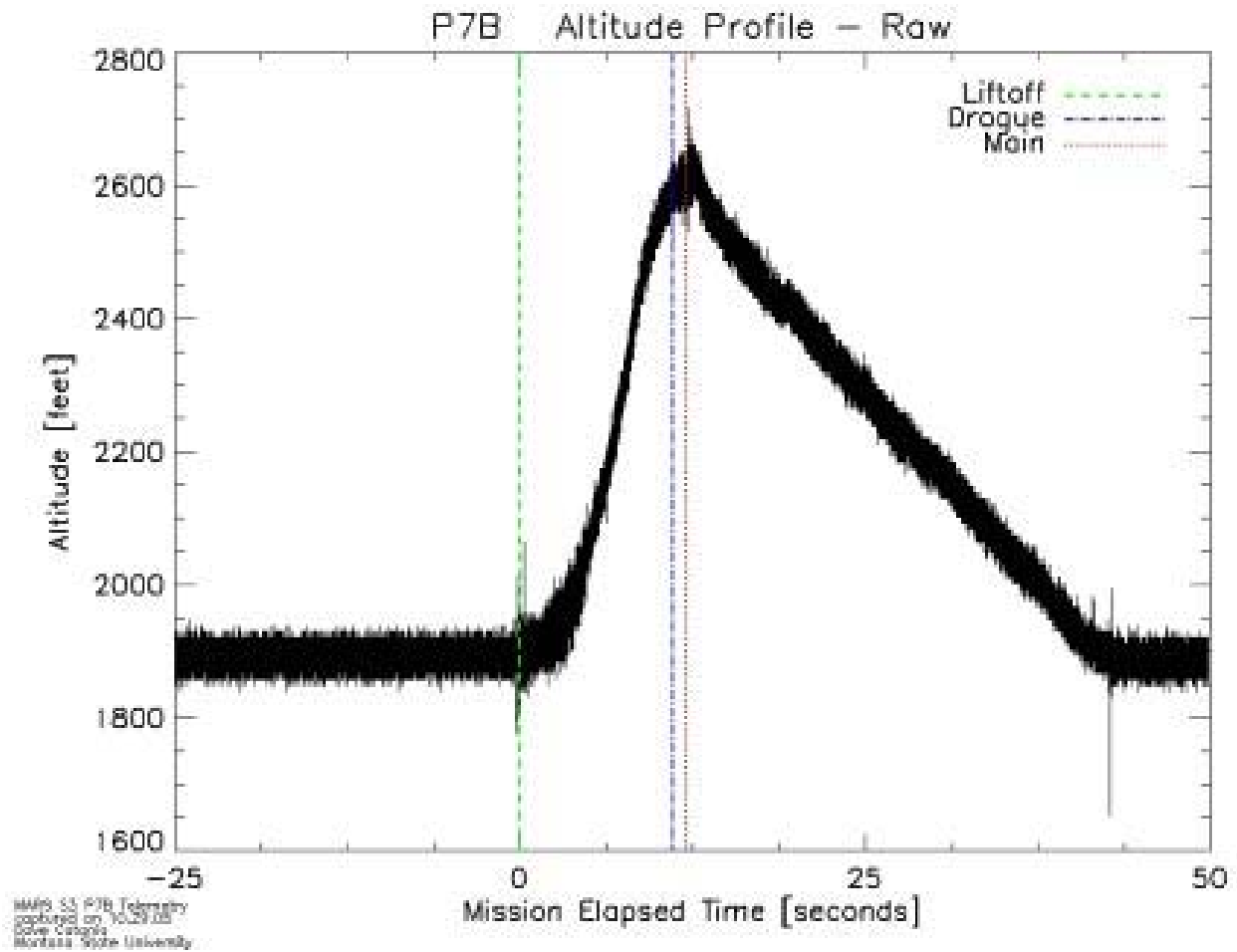


Figure 14: P-7B Altitude Profile Acquired by MSU Data Logger

2.6 Follow-on RLV Concept Definition and Test Planning

2.6.1 Next Generation NLV Prototypes

The plan generated for the Phase II Fast Track proposal envisions two vehicles for follow-on flight testing. The first is the refurbished P-7 for pathfinding the transition to and continued evaluation of RLV turn-around operations on a government launch range. At the time of this report, the Navy's San Clemente Island is the leading candidate site for such operations. Enhancements to the P-7 might include new payloads and/or an iteration of the Wi Fi experiment.

The second test RLV, tentatively assigned the title of Prospector 9 (P-9), is a next-generation first stage prototype that shares the same outer geometry as the P-7 but features much higher performance capability that approaches that of the envisioned operational ENLV. Major design enhancements include full-scale, high-margin propellant tanks, a full-thrust engine and thrust vector control. The latter is critical to enabling relatively low thrust-to-weight ratios at launch and therefore much greater propellant loads. It also potentially enables the elimination of the requirement for a launch rail, which would simplify ground operations. An early round of flight tests will continue the focus on reusability and rapid turn-around operations, while a subsequent test campaign will begin the pursuit of high altitude (> 50 nautical miles) RLV flights.

2.6.2 Hybrid NLV Concept

Part of the definition study of follow-on RLV concepts addressed a full-scale system featuring a reusable first stage and expendable second stage that could implement the same mission (10 kg to a 250 km polar orbit) as that baselined for the fully expendable NLV. A primary guideline for comparative assessments of this "hybrid nanosat launch vehicle" (HNLV) relative to the ENLV was that the second stage would be common to both configuration types. The motivations for this constraint were two fold - it narrowed the focus of the study and it is consistent with an incremental programmatic approach to achieving an operational HNLV. Relative to the latter, it is anticipated that the baseline ENLV could enter service first, pathfinding operations and establishing the viability of this niche. The reusable first stage would then follow upon completing development and qualification.

Figure 15 compares the dry weight of the HNLV first stage with that of an expendable one, as a function of the structural mass fraction. For this first-order approximation, it is assumed that the target mass fraction for the reference ENLV - 13.1% - is retained for the comparable systems on the HNLV first stage. The comparative increase in the total HNLV mass fraction is therefore attributed to the addition of new systems for recovery, landing and reuse. Thus, at a mass fraction of 22%, the HNLV first stage weight approaches 1475 lbm - almost four times that of the ENLV stage, with approximately 600 lbm being allocated to the recovery and landing functions. The growth in overall GLOW of the HNLV versus the ENLV is only a factor of two (Figure 16).

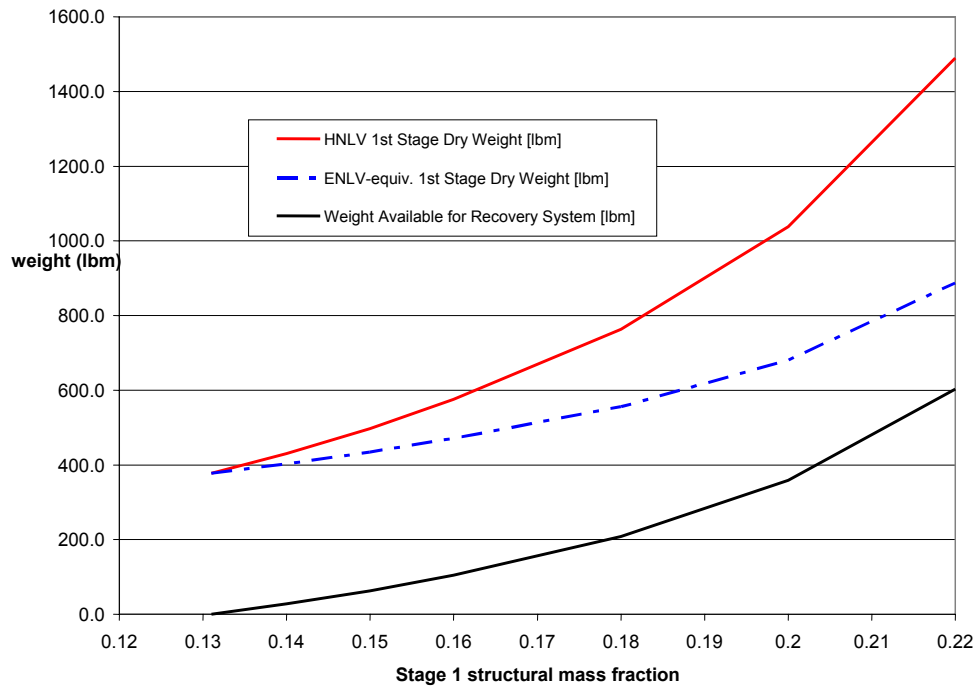


Figure 15: HNLV First Stage Weight as a Function of Structural Mass Fraction

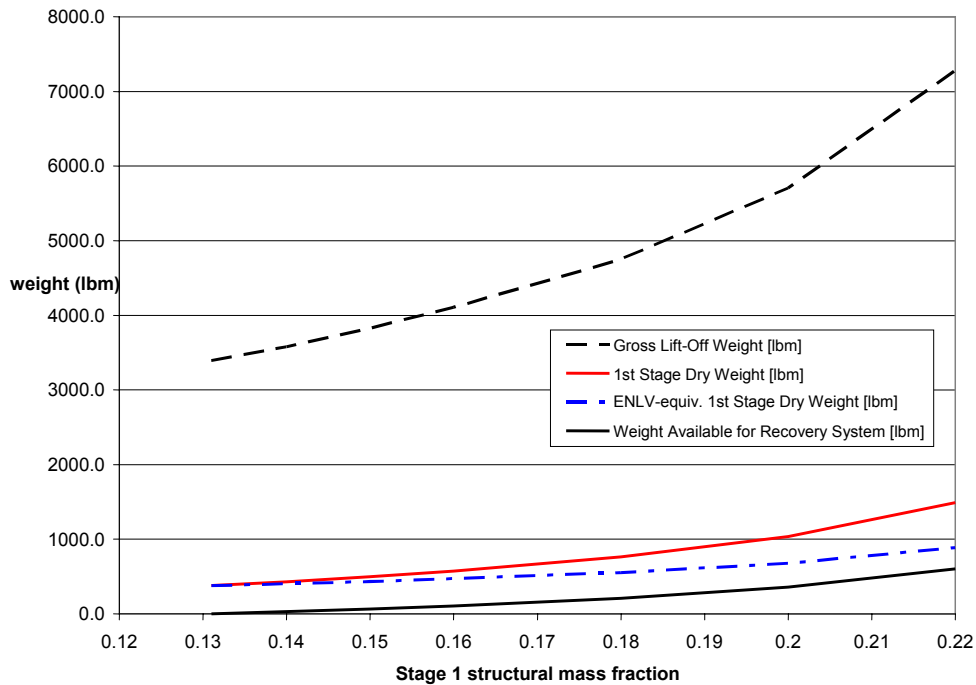


Figure 16: HNLV Liftoff Weight as a Function of First Stage Structural Mass Fraction

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Table 7. Twice-Heavier HNLV Characteristics and Performance (ENLV First Stage Shown for Reference)

	HNLV 1st Stage	ENLV 1st Stage	2nd Stage
Dry mass	676 kg (1489 lbm)	171 kg (378 lbm)	30 kg (66 lbm)
Stage inert mass fraction	0.22	0.131	0.137
Chamber pressure	2 MPa (300 psi)	2 MPa (300 psi)	1 MPa (150 psi)
Sea-Level Thrust	42,900 N (9,641 lbf)	20,000 N (4,500 lbf)	N/A
Sea-Level Specific Impulse (ISP)	212 s	212 s	N/A
Vacuum Thrust	29,600 N (6,660 lbf)	29,600 N (6,660 lbf)	1,900 N (430 lbf)
Vacuum ISP	314 s	314 s	347 s
Separation/burnout time (from liftoff)	117 s	117 s	445 s
Separation/burnout altitude	54 km	54 km	250 km, orbital

The next step in assessing and comparing the relative economic feasibility of these ENLV and HNLV concepts will require coordinated assumptions on launch rates (both civilian and Department of Defense (DOD)) and the nature of these anticipated missions. A scenario in which there are only several missions per year, each unique, contrasts greatly with one based on frequent (i.e. - monthly or even weekly) flights to a common set of standard orbits that have already been coordinated with and pre-approved by all involved regulatory agencies. The former presents the case for most present launch services and for which empirical market data is available and the lower development costs have universally favored expendable configurations. The latter case is more typical of the passenger and cargo airline markets and is expected to be more amenable to reusable/refurbishable vehicle concepts like the HNLV.

The degree of "responsiveness," or quick reaction capability also needs to be considered, in terms of "call-up" time to initial launch and the available turn-round time between subsequent flights. From a cost perspective, it is anticipated that the extent of on-site facilities, vehicle inventory, consumables and personnel will increase inversely to the required call-up time for launch.

GSC will continue to address these feasibility issues jointly with AFRL/PR and the Space and Missile Systems Center during Phase II for inputs relative to candidate DOD-based NLV missions sets as part of our ongoing commercialization activity.

2.6.3 Hybrid Small Launch Vehicle Performance

A brief analysis extended the scope of this sizing trade to a lower-end "small launch vehicle" (SLV). This baseline expendable SLV (ESLV) is assumed to have the same characteristics as the ENLV while being capable of delivering an order of magnitude more payload (i.e. - 100 kg) to the reference 250 km polar orbit. Here, most non-dimensional parameters such as thrust-to-weight ratio and first-to-second stage weight ratio were kept constant when scaling from the ENLV to the ESLV. The major difference with the ENLV in those parameters is the larger allowable inert mass fraction for the second stage (Table 8) owing to the slightly reduced drag, namely 14.9% for the ESLV second stage instead of 13.7% for the ENLV. Note that some of this increase in allowable dry mass could be allocated to the first stage. Such analyses would be the subject of trade studies beyond the scope of the present work.

Table 8. Expendable SLV Characteristics and Performance – 100 kg to LEO

	1st Stage	2nd Stage*
Dry mass	1715 kg (3780 lb)	329 kg (726 lb)
Stage inert mass fraction	0.131	0.149
Chamber pressure	2 MPa (300 psi)	1 MPa (150 psi)
Sea-Level Thrust	200,000 N (45,000 lbf)	N/A
Sea-Level ISP	212 s	N/A
Vacuum Thrust	296,000 N (66,600 lbf)	19,000 N (4,300 lbf)
Vacuum ISP	314 s	347 s
Separation/burnout time (from liftoff)	117 s	445 s
Separation/burnout altitude	54 km	250 km, orbital

** an initial assumption requiring verification is that the ballistic coefficient and mass of the second stage are low enough to achieve a sufficiently high probability that the stage will fully burn-up upon reentry to the atmosphere at any point after stage separation. Consequently, no dedicated, stage-specific safing capability is required.*

Similarly to the case of the HNLV, the use of a recovery and landing system in a hybrid SLV (HSLV) requires additional mass relative to the entirely expendable configuration. Figure 18 shows the increase in SLV first stage dry mass and mass available for the first stage recovery system as a function of stage's structural mass fraction while Figure 19 presents the comparison between GLOW for the expendable and hybrid SLVs. The results are very similar for the HNLV and HSLV with some differences at the larger structural mass fractions due to aerodynamic effects (unlike mass which scales with respect to volume, drag scales with respect to area). The scale of the HSLV mandates a very different logistics and launch operations environment from that of an HNLV.

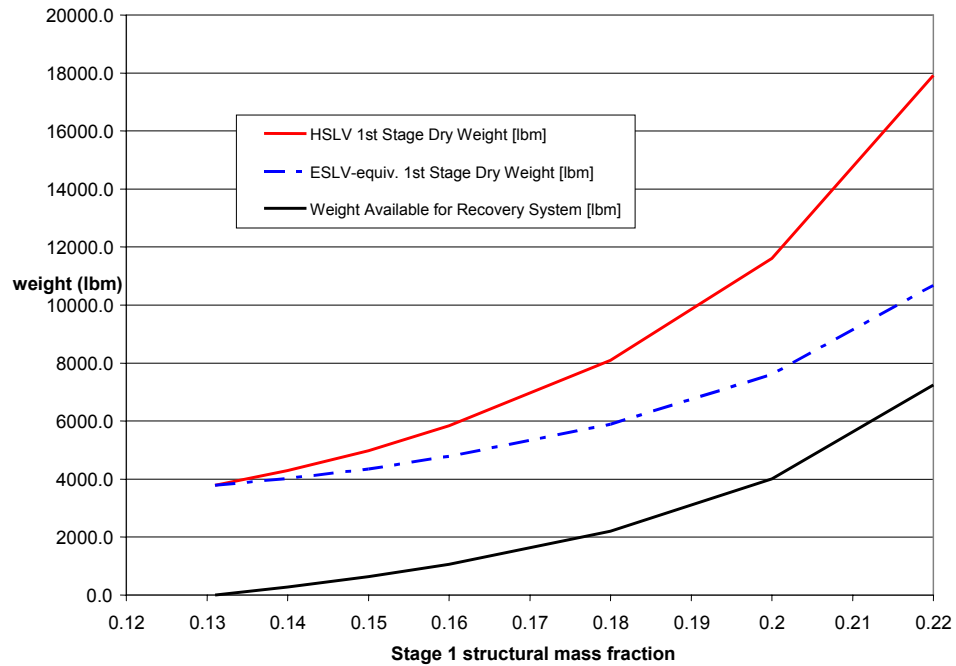


Figure 18: HSLV First Stage Weight as a Function of Structural Mass Fraction

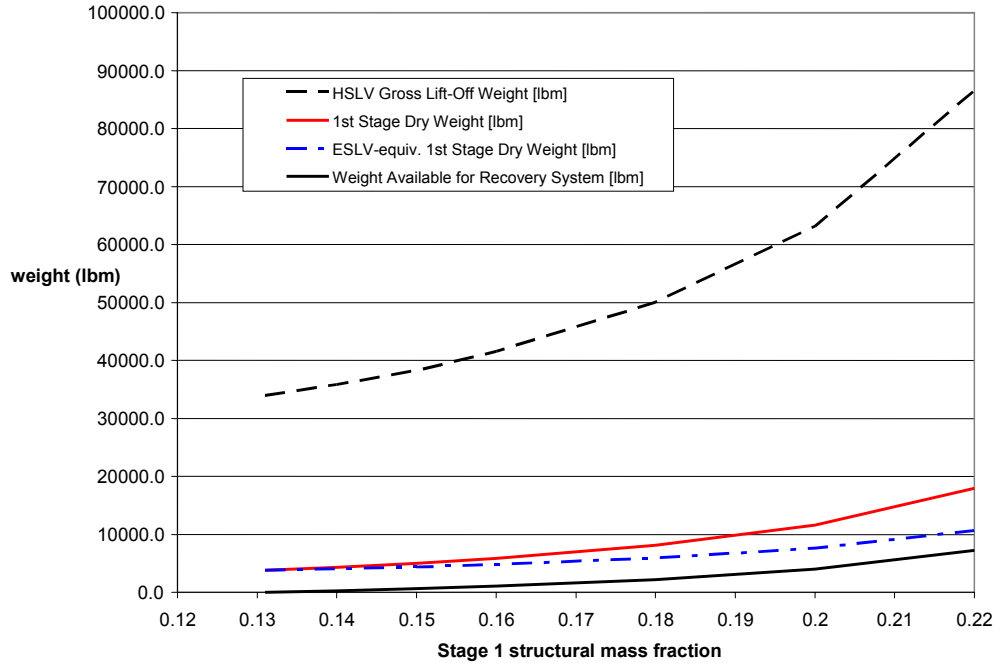


Figure 19: HSLV Liftoff Weight as a Function of First Stage Structural Mass Fraction

2.6.4 Impact of Fuel Selection on Hybrid NLV Turn-Around Processing Times

Present NLV prototypes feature denatured ethanol for fuel due to its ease of handling and benign characteristics. The reference NLV concept utilizes cryogenic propylene to achieve higher specific impulse while maintaining a density comparable to that of RP-1. Propylene also is environmentally benign compared to RP-1 and easier to handle than hydrogen.

In general, cryogenic fuels (propylene, methane or hydrogen) are preferred for vehicle turn-around operations because they reduce or even eliminate many of the cleaning requirements that are associated with kerosene-type propellants. Besides the time required for such cleaning tasks, they are also inherently manually intensive and present quality control challenges. Even a very minimal amount of contamination can lead to the loss of an entire vehicle. Furthermore, the solvents employed for such cleaning tasks are themselves a concern from both safety and environmental hazard perspectives. By contrast, nitrogen purging of a cryogenic system is simple and cost-effective (in the case where liquid hydrogen may still be in the system, it could prove necessary to switch to helium instead for such purging and inerting operations).

Any disadvantages associated with extended chilling times and boil-off during propellant loading and on-the-pad holds are manageable with appropriately designed ground support equipment. Such installations for cryogenic fuels in general will require a system for handling vent gases from the vehicle and a combination of leak monitoring, flame detection and fire suppression capabilities - all of which involve available technologies and capabilities that have been proven in multiple launch site applications since the 1960s. In the specific case of densified propylene, such equipment will also feature a refrigeration unit to liquefy and cool this fuel. While not yet demonstrated in a launch environment, such a refrigeration unit can be implemented with standard components and technologies from the industrial gases industry.

3.0 CONCLUSIONS AND RECOMMENDATIONS

This test activity has provided preliminary validation for the following assumptions that have been the basis for the Phase I effort:

- responsive, fast turn-around flight operations are feasible with an extremely simple RLV configuration that features a subset of low-cost components that can be easily and quickly removed and replaced between flights
- implementing initial RLV operations with smaller systems (i.e. - NLV-sized launchers) significantly reduces the requirements for extensive investments in ground support equipment and associated range infrastructure.

In addition, the successful re-flights of both the MSU data logger and the Cal Poly P-POD CubeSat deployer demonstrated that a "munitions" approach to payload design and accommodations is compatible with such fast turn-around operations.

It was the consensus conclusion of the test team that with refined procedures, improved definition of roles and responsibilities, and additional sets of replacement hardware, it should be possible to both further reduce the turn-around time between flights with the existing prototype RLV (i.e. - the P-7), and to also conduct more than two flights during a single day. A key factor would be extending the site preparation period to at least several days, so that team members are rested and focused on launch day. Another effective change would be to re-schedule post-test recovery and clean-up activities and subsequent shipment of the vehicle and equipment back to Long Beach to the following day, rather than performing these tasks immediately after the last flight test. Such recommendations have less relevance for longer-term operational scenarios based on semi-permanent facilities and on-site hardware and equipment storage.

While there is value in attempting to improve the turn-around processing times and processes demonstrated with these first P-7 flight tests, it is equally important to continue extending the realm of pathfinder test operations to additional mission phases and environments that are anticipated for the full-up orbital HNLV, using higher-fidelity hardware. The Phase II follow-on activity will address these by conducting initial flight operations from a government facility and transitioning to a higher-performance first stage prototype. Another near-term activity that is not yet been baselined in planning but has potential would be to conduct ocean-based recovery simulations with non-flight hardware.

Relative to vehicle capabilities, implementing thrust vector control with the associated guidance, navigation and control capabilities is the biggest technical step to NLV orbital missions (for both expendable and hybrid configurations). Providing a flight termination system that complies with range safety requirements at a feasible cost is the other major challenge.

REFERENCES

- ¹ Garvey, J., Brooks, L. and J. Puig-Suari, " Responsive Payload Accommodations and Integration Operations for Dedicated CubeSat Missions," paper no. AIAA-RS4 2006-7002, 4th Responsive Space Conference - 2006, Los Angeles, CA, 24 - 27 April 2006

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